The Luminosity Function of the Brightest Galaxies in the IRAS Survey

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ABSTRACT. Results from a study of the far infrared properties of the brightest galaxies in the IRAS survey are described. There is a correlation between the infrared luminosity and the infrared to optical luminosity ratio and between the infrared luminosity and the far infrared color temperature in these galaxies. The infrared bright galaxies represent a significant component of extragalactic objects in the local universe, being comparable in space density to the Seyferts, optically identified starburst galaxies, and more numerous than quasars at the same bolometric luminosity. The far infrared luminosity in the local universe is approximately 25% of the starlight output in the same volume.

1.0 INTRODUCTION

The IRAS survey was the first infrared all sky survey with sufficient sensitivity to detect a significant number of extragalactic sources. To understand the significance of the infrared emission from galaxies it is important to establish a census of the kinds of galaxies that are significant infrared emitters, to determine the space densities of these galaxies, and to compare infrared bright galaxies with other known classes of extragalactic objects.

We have begun a program to understand the properties of the brightest infrared galaxies discovered in the IRAS survey. This paper derives the far infrared luminosity function of this sample of galaxies. A preliminary description of the luminosity function for the most luminous members of this sample was reported by Soifer, *et al.* (1986a), while a detailed description of the entire sample is given by Soifer, *et al.* (1986b).

2.0 THE IRAS BRIGHT GALAXY SAMPLE

The objects selected for study in this survey were chosen to be a complete sample of far infrared emitting extragalactic objects. The final criteria defining the IRAS bright galaxy sample were all extragalactic objects having $60\mu m$ flux densities greater than 5.4 Jy and galactic latitude $|b| > 30°$. The area of sky where complete redshift information was obtained for candidate objects placed further areal constraints on the sample: Declination $\geq -30°$ for 0-12 hr, $\geq -15°$ for 12-14 hr, and $\geq -20°$ for 14-24 hrs.

The final sample was selected to be all extragalactic sources meeting the above constraints selected from the IRAS Point Source Catalog (1985), the Catalog of Small Scale Structures (1986), and the Catalog of IRAS Observations of Large Galaxies (Rice, *et al.* 1986). As would be expected, the data sampling the largest spatial scales always provided the largest $60\mu m$ flux density.

The total area covered in the Bright Galaxy survey is ~14,500 square degrees. There are 324 objects in the sample; 29 galaxies have $60\mu m$ flux densities taken from the Large Galaxy Catalog, 53 have $60\mu m$ flux densities taken from the Small Scale Structures Catalog, with the rest taken from the Point Source Catalog.

3.0 BASIC PROPERTIES OF THE BRIGHT GALAXY SAMPLE

The properties of the IRAS Bright Galaxy sample are important for describing the far infrared characteristics of the local Universe. A basic question is to determine the kind of objects contained in the sample. Although no morphological criterion was established for an object to be in the Bright Galaxy sample the vast majority of objects in the sample are cataloged galaxies. Furthermore only one object in the sample, IR0518-25 (Sanders, *et al.* 1986),

shows a predominantly stellar appearance on visible images. This object (described in detail by Sanders, *et al.*) has, in addition, broad emission lines and is clearly a Seyfert nucleus. Thus virtually all the infrared bright extragalactic objects in the local Universe are associated with galaxies.

All the galaxies in the Bright Galaxy sample have far infrared flux densities much greater than can be expected from a stellar population. None are known radio loud objects where the infrared emission could be expected to be an extension of a radio non-thermal source. Thus we assume that the far infrared peak in the energy distribution is due to thermal emission by dust.

The galaxies in the Bright Galaxy sample range in distances from 0.7 Mpc for M33 to >300 Mpc. The median distance is 32 Mpc, excluding Virgo galaxies. Thus the IRAS Bright Galaxy sample extends well beyond the local supercluster, but is not sampling objects at distances significant with respect to the size of the Universe, i.e. the sample is one of the far infrared properties of the local Universe. A total of 31 sample galaxies were identified as associated with the Virgo cluster. While the Virgo cluster presents a significant contribution to the Bright Galaxy sample, it by no means dominates the sample.

The range of observed far infrared luminosities extends from $\sim 10^8 L_\odot$ to $> 10^{12} L_\odot$, with the peak in the distribution occurring at $\sim 2 \times 10^{10} L_\odot$. For the IRAS Bright Galaxies the range in values of $\log(f_{ir}/f_b)$ is from -1 to 2.1, with a median value of $\log(f_{ir}/f_b)$ of 0.4, where f_{ir} is the far infrared flux from the galaxy, and f_b is the flux in the blue, defined as νf_ν (blue). This value is much greater that the corresponding value of $\log(f_{ir}/f_b)$ of $\sim$ -0.2 for an optically selected sample of galaxies. The infrared flux limited sample selects galaxies with much greater average infrared luminosity per unit blue luminosity than does a magnitude limited optical sample.

Figure 1 shows that f_{ir}/f_b correlates with L_{fir}, while there is no correlation between f_{ir}/f_b and L_b. The simplest explanation of this correlation is that the far infrared and blue luminosity components are uncorrelated, and the blue luminosities of the galaxies in the bright galaxy sample are roughly constant. Thus a larger f_{ir}/f_b ratio requires larger L_{fir} rather than extinction depressing the blue light. The absence of galaxies in the region of Figure 1 where $L_{fir} < 10^{10} L_\odot$ and $f_{ir}/f_b > 10$ shows that there are no dwarf galaxies in the Bright Galaxy sample with large f_{ir}/f_b ratios.

In Figure 2 the $60\mu m/100\mu m$ flux density ratio (effectively color temperature) is plotted vs far infrared luminosity. There is a correlation between the color temperature and the far infrared luminosity in the sense of higher luminosities generally implying higher $60\mu m/100\mu m$ color temperatures, while there is no correlation between the far infrared color temperature and the blue luminosity. The lack of correlation between far infrared color temperature and blue luminosity further supports the lack of coupling between the blue and far infrared luminosity components in these galaxies.

4.0 LUMINOSITY FUNCTION OF IRAS GALAXIES

The $60\mu m$ luminosity function derived from the Bright Galaxy sample is shown in Figure 3. Other $60\mu m$ luminosity functions have been derived based on other samples from the IRAS data (e.g. Lawrence, *et al.* 1986, Rieke and Lebofsky, 1986). We have compared these luminosity functions with that derived for the Bright Galaxy sample, and show this comparison in Figure 3. Here we have converted all the luminosity functions to the units used here, i.e. the bins represent the space density in galaxies per cubic megaparsec per magnitude interval in $60\mu m$ luminosity, where the $60\mu m$ luminosity is taken as $\nu L_\nu(60\mu m)$, and H_o is taken as 75 Km s^{-1} Mpc^{-1}. As can be seen from Figure 3 the agreement between the three luminosity functions, derived from completely different samples is excellent.

Two power laws, fit to the observed $60\mu m$ luminosity function, are shown in Figure 3. At low luminosity the best fit power law gives a slope $\rho \sim L^{-0.83}$, while at high luminosity the best fit slope is $\rho \sim L^{-2.05}$. The luminosity of the break between the two power laws is $\sim 2 \times 10^{10} L_\odot$. For comparison a Schechter function is also fit to the observed luminosity function.

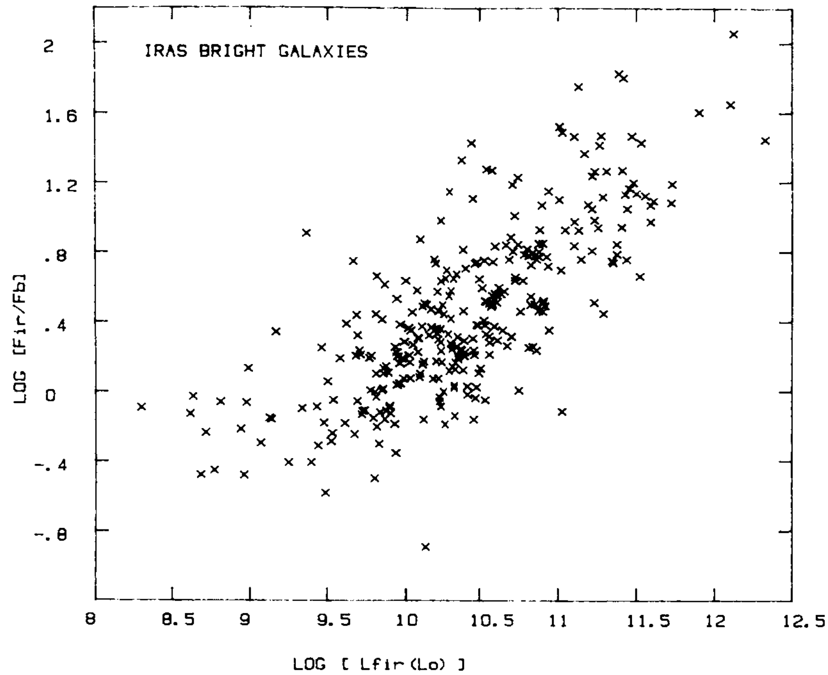

Figure 1: The ratio of the far infrared to blue flux plotted vs the far infrared luminosity for the galaxies in the Bright Galaxy Sample. The far infrared flux represents the integral of a single temperature Planck curve, convolved with an emissivity proportional to frequency, and fitted to the observed flux densities at 60μm and 100μm. The blue flux is taken to be νf_ν (blue). The luminosities were calculated using a Virgocentric velocity field where D_{Virgo} = 17.6 Mpc and H_o = 75 km $s^{-1}Mpc^{-1}$ at large distances.

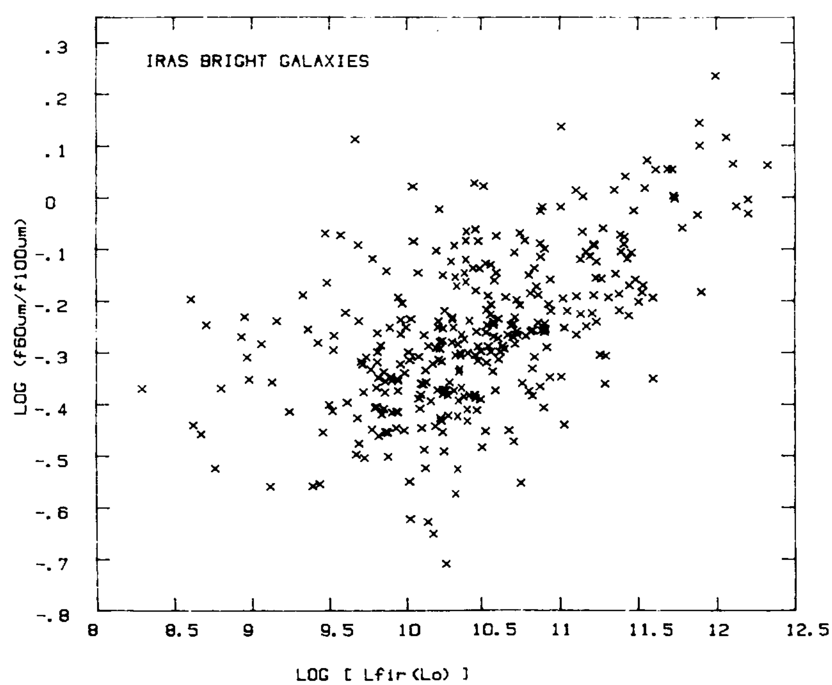

Figure 2: The ratio of the 60μm to 100μm flux densities plotted vs far infrared luminosity for the galaxies in the Bright Galaxy Sample.

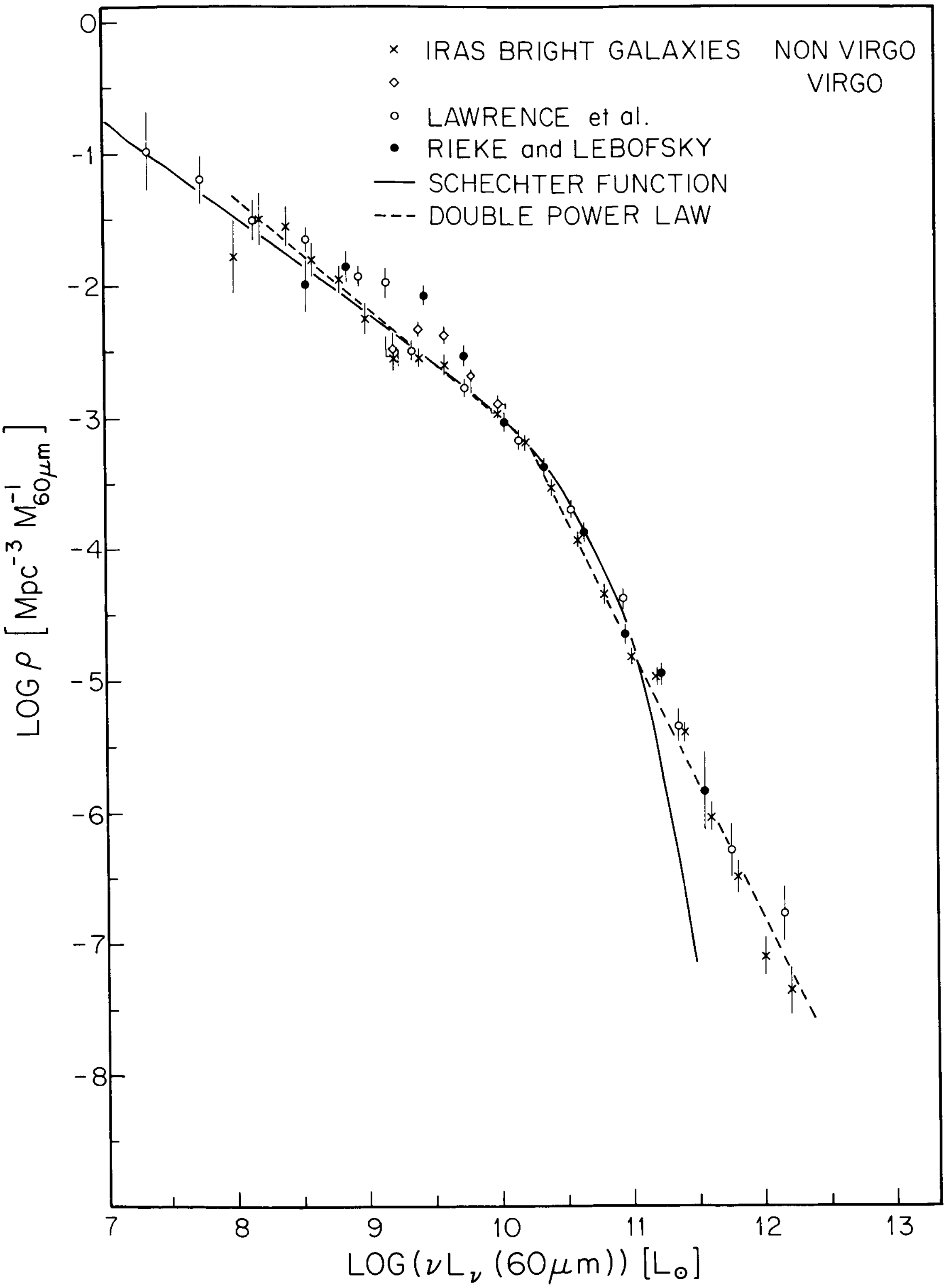

Figure 3: The 60μm luminosity function derived for the Bright Galaxy sample, plotted as space density in galaxies per cubic Megaparsec per magnitude range in 60μm luminosity vs 60μm luminosity. The 60μm luminosity is taken as νL_ν (60μm). For comparison the luminosity functions derived from different IRAS samples are shown as well. These are taken from Lawrence, *et al.* 1986 and Rieke and Lebofsky, 1986. Both a double power law and a Schechter type luminosity function are shown for comparison with the observed luminosity functions.

While the strict definition of the $60\mu m$ luminosity function is most appropriate for comparing the local luminosity function with the deeper surveys with IRAS (e.g. Hacking and Houck, 1986) and ultimately next generation space missions, one of the more immediate goals of the present study is to understand the significance of far infrared emission in the local Universe. This requires comparing the space densities of widely varying classes of objects. To do this in a meaningful way we have chosen to paramaterize the luminosities of objects by the bolometric luminosity. In Figure 4 the luminosity functions of a variety of different important classes of extragalactic objects are plotted. The far infrared luminosity has been adopted as the bolometric luminosity for the IRAS Bright Galaxy sample. The total far infrared luminosities calculated in this way are about 50 percent greater than the $60\mu m$ luminosities for the same galaxies.

For comparison with the luminosity function for the Bright Galaxy sample, luminosity functions taken from the literature for "normal galaxies," "starburst galaxies," Seyfert galaxies and quasars are included in Figure 4. The published luminosity functions are given in terms of M_b, i.e. absolute blue luminosity, and thus a different bolometric correction was estimated for each of the classes of objects. These corrections are described in detail in Soifer, 1986a,b.

Figure 4 shows that the infrared bright galaxies represent a significant component in the local Universe, being more numerous than all categories of extragalactic objects at very high luminosites, and more numerous than all except normal galaxies at those luminosities where normal galaxies contribute significantly to the global luminosity function.

The infrared galaxies are more numerous than (non-Seyfert Markarian) starburst galaxies at all luminosities. In the range $10^{10}L_\odot$ to $10^{11}L_\odot$, the two become quite comparable. As suggested by Soifer, *et al.* 1986a, this agreement suggests that these represent the same population, at least over this luminosity range. At higher luminosities the infrared selected galaxies become significantly more numerous than the starburst galaxies, suggestive of either dust affecting the UV selection of the more luminous Markarian galaxies, or possibly a new luminosity component becoming important at the highest luminosities.

Below $\sim 2 \times 10^{11}L_\odot$, normal galaxies dominate the space densities of objects in the local Universe. For luminosities above $\sim 2 \times 10^{11}L_\odot$ infrared luminous galaxies appear to be the dominant population in the local Universe, having virtually the same space densities as the Seyferts at the lower end of this range, and a significantly greater space density than quasars at the higher luminosities. How high the far-infrared luminosity function extends will await a survey of sufficient numbers of IRAS galaxies to be able to make a statistically significant statement on the content of the next luminosity bin.

From the luminosity functions the contribution to the luminosity density of the local Universe can be estimated. The galaxies with far infrared luminosites greater than $10^8L_\odot$ produce roughly $9 \times 10^7 L_\odot/Mpc^3$ in far infrared emission, with $4 \times 10^7 L_\odot/Mpc^3$ being generated in galaxies with luminosities greater than $10^{10}L_\odot$. By comparison the normal galaxies produce a bolometric luminosity density of $\sim 4 \times 10^8 L_\odot/Mpc^3$, where the integrated blue luminosity density was taken from Felten (1977) and Yahil, Sandage, and Tammann (1980), corrected to bolometric luminosity and to H_o=75 Km s^{-1} Mpc^{-1}. Thus ~25 percent of the stellar luminosity luminosity of galaxies emerges in the far infrared. At luminosities greater than $\sim 10^{10}L_\odot$ it is likely than star formation is the dominant form of energy generation in infrared bright galaxies (this volume) at least until the very highest luminosities. Several authors (Persson and Helou, 1986, Helou, 1986, Rowan-Robinson, 1986, de Jong and Brink, 1986) have suggested that a significant fraction of the far infrared luminosity in less active galaxies is recycled stellar radiation not necessarily associated with star formation regions. Thus overall, star formation accounts for between 60 and 80 percent of the far infrared luminosity generated in the local Universe.

The total space density of galaxies with far infrared luminosities $> 10^{11}L_\odot$ is $\sim 2.2 \times 10^{-5}$ Mpc^{-3}. Figure 1 shows that 85 percent of these galaxies have blue luminosities $> 10^{10}L_\odot$. From Christensen (1975) the space density of normal galaxies with $L_b > 10^{10}L_\odot$ is 3.4×10^{-3}, or roughly 0.6 percent of the galaxies with $L_b > 10^{10}L_\odot$ have $L_{fir} > 10^{11}L_\odot$. If the infrared bright phase has a lifetime t_{ir} and the optical phase has a lifetime t_b then the fraction of galaxies that have undergone such an infrared active phase is $0.006 \times t_b/t_{ir}$. If $t_b \sim 10^{10}$ yrs, and the infrared bright phase is a starburst phase with $t_{ir} < 10^8$ yrs (Rieke, *et al.* 1980, Gerhz, Sramek, and Weedman, 1983) then

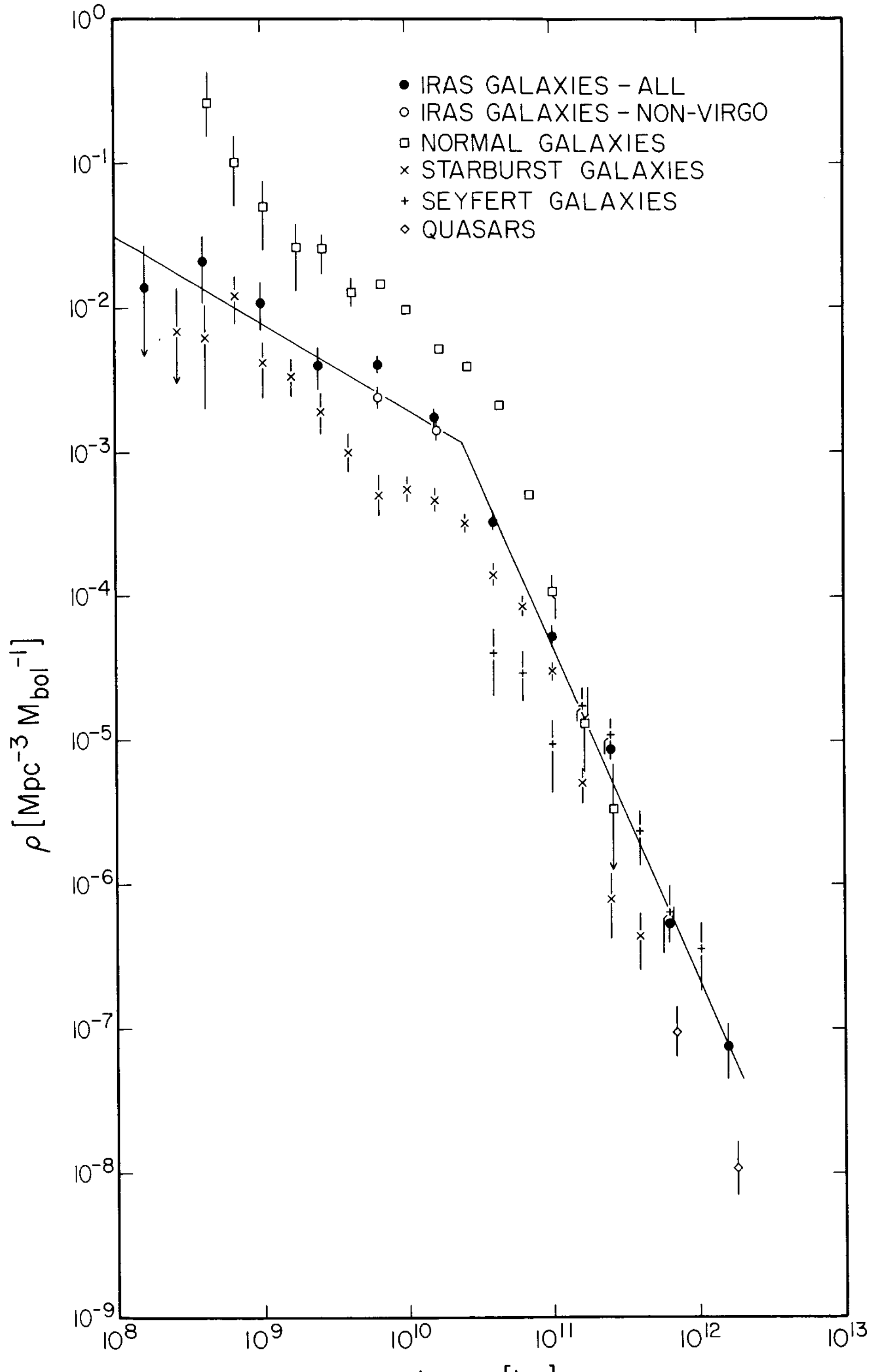

Figure 4: The far infrared luminosity function is shown for the Bright Galaxy sample, along with luminosity functions of a variety of classes of extragalactic objects, where the luminosity functions for the other classes of objects have been converted to bolometric luminosity.

a significant fraction, perhaps approaching 50 percent, of galaxies with $L_b > 10^{10}L_{\odot}$ must have undergone such an infrared active period over the course of their evoulution, if this is a non- recurring event stage in galaxy evolution.

5.0 Acknowledgements

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6.0 References

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DISCUSSION

BECKLIN:

Is there any reason to suspect that the infrared luminosity function drops off at $L > 10^{12}\ L_{\odot}$ and thus drops below the QSO function?

SOIFER:

Not yet. This will require statistically complete redshift surveys of several thousand IRAS catalog galaxies to extend the $60\mu m$ luminosity function to greater luminosities than $\sim 2 \times 10^{12}\ L_{\odot}$.

LOW:

Why have we not found galaxies more luminous than Mkn231?

SOIFER:

Based on our Bright Galaxy luminosity function we would predict $\sim$3 objects with far-infrared luminosity about 1 magnitude more luminous than Mkn231. We found no objects in that bin. Others have found individual objects having higher luminosity than Mkn231 in the IRAS survey (e.g., Mkn1014, 3C48, etc.) Until a large enough sample can be surveyed, where the number of sources at these luminosities is significant, we will not know whether there is a real cut off in the luminosities of IRAS galaxies.

ROCHE:

We have been taking optical spectra at the AAT of faint IRAS galaxies with no identified counterparts on the Sky Survey, and some of those have redshifts in the range 0.2-0.3. Even with fluxes of approximately 1 Jy at 60μm they have luminosities a few times greater than that of Mkn 231.

WINDHORST:

Given the apparently good correlation between 60μm flux and 21 cm continuum flux for spiral galaxies, did you translate your 60μm luminosity function to 21 cm and how does it compare with, for instance, Hummel's 21 cm radio luminosity function of spiral or interacting galaxies?

SOIFER:

Hacking has done this and finds excellent agreement between the 60μm source counts and the radio source counts for spirals done by Condon.